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DIRECT DETERMINATION OF WIND SHEARS FROM THE GRADIENTS OF SATELLITE RADIANCE OBSERVATIONS

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FINAL TECHNICAL REPORT

BY

George Ohring, Principal Investigator
Binyamin Neeman

November 1980

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EUROPEAN RESEARCH OFFICE

United States Army
London, England.
GRANT NUMBER DA-ERO-77-G-051

Department of Geophysics and Planetary Sciences
Tel Aviv University, Ramat Aviv, Israel

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To the extent that the wind field is close to geostrophic, the thermal wind is a good approximation to the vertical wind shear (vertical variation of the horizontal wind). And since the thermal wind is proportional to the horizontal temperature gradient, the possibility exists of determining it from satellite radiance observations. Several different methods are developed for retrieving thermal winds directly from the horizontal gradients of satellite radiance observations. The methods are applied to the determination

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of thermal winds in the upper troposphere and lower stratosphere over the White Sands Missile Range area. A special series of about 30 concurrent sets of radiance observations from the NOAA-4 VTRR instrument and wind shears from radiosonde observations, distributed throughout one year, is used for these tests. The results obtained with these direct methods are compared with results obtained with:

1) a traditional method, in which temperature profiles are first retrieved from the satellite radiances and the thermal winds are then obtained from the horizontal gradients of the retrieved temperatures, and 2) a linear regression between observed radiance gradients and observed wind shears. The latter method serves as an estimate of the upper limit of accuracy to be obtained by any method based on a linear combination of radiance gradients.

The results indicate that the direct methods may be divided into two groups, with much better retrievals for one of these groups. The probable reasons for these differences are identified. The best direct methods yield results comparable to the traditional method, but none of the methods - not even the regression technique - is particularly skillful. The lack of skill in these particular cases is attributed mainly to the errors associated with trying to measure relatively small horizontal radiance gradients over relatively small horizontal distances.

Foreword

This report contains a full description of our work on the Direct Determination of Wind Shears from the Gradients of Satellite Radiance Observations plus reprints of our paper on the Impact of Satellite Temperature Sounding Data on Weather Forecasts. The latter study was partially supported by the Grant.

ABSTRACT

To the extent that the wind field is close to geostrophic, the thermal wind is a good approximation to the vertical wind shear (vertical variation of the horizontal wind). And since the thermal wind is proportional to the horizontal temperature gradient, the possibility exists of determining it from satellite radiance observations. Several different methods are developed for retrieving thermal winds directly from the horizontal gradients of satellite radiance observations. The methods are applied to the determination of thermal winds in the upper troposphere and lower stratosphere over the White Sands Missile Range area. A special series of about 30 concurrent sets of radiance observations from the NOAA-4 VTPR instrument and wind shears from radiosonde observations, distributed throughout one year, is used for these tests. The results obtained with these direct methods are compared with results obtained with:
1) a traditional method, in which temperature profiles are first retrieved from the satellite radiances and the thermal winds are then obtained from the horizontal gradients of the retrieved temperatures, and
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The results indicate that the direct methods may be divided into two groups, with much better retrievals for one of these groups. The probable

reasons for these differences are identified. The best direct methods yield results comparable to the traditional method, but none of the methods - not even the regression technique - is particularly skillful. The lack of skill in these particular cases is attributed mainly to the errors associated with trying to measure relatively small horizontal radiance gradients over relatively small horizontal distances.

Table of Contents

1. Statement of the Problem

For purposes of predicting the nuclear fallout pattern associated with the use of tactical nuclear weapons in the battlefield, it is necessary to know the vertical distribution of the horizontal wind from the surface of the earth to an altitude of about 30 km. In principle, conventional radiosonde (rawinsonde) observations could be used for supplying all of the required wind information; however, it is not particularly desirable to use the radiosonde system for determining the wind field above 15 km for the following reasons:

1) No other Army battlefield requirement exists for meteorological data above 15 km. The nuclear fallout prediction requirement imposes a substantial increase (over that required for the 0-15 km observations) in meteorological equipment, operations and manhours on the battlefield.

2) Large errors are possible at high altitudes, partly because of wind measurement errors caused by tracking difficulties at the low elevation angles associated with strong winds, and partly because of space and time variability inherent in the data. Because of balloon trajectories, the locations of the measurements at altitudes of 20 to 30 km are frequently 100 to 150 km from the radiosonde balloon launch site.

To overcome these problems associated with the use of radiosondes for wind information above 15 km, it has been suggested[1] that a mix of conventional radiosonde and satellite radiance observations be used to supply all of the required information: the radiosonde would provide the wind field to 15 km and the satellite would supply the wind information for the 15 to 30 km layer (which for our purposes we may call the stratosphere).

The concept of using satellite observed radiances to infer horizontal winds in the stratosphere is based on the following physical principles:

1) the satellite observed spectrum of radiance above a particular point on the earth's surface depends upon the vertical temperature profile above that point.
2) the vertical variations of the horizontal wind (windshears) are directly related to the horizontal gradients of atmospheric temperature.

From (1) and (2), one can, in principle, estimate the windshears from the horizontal gradients of satellite observed radiances.

The use of satellite radiance observations for determining stratospheric wind shears is particularly attractive due to the absence of clouds (which interfere with retrievals of temperatures) in the stratosphere.

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1 Duncan, L.D., 1977: SATFAL - The application of meteorological satellite data to nuclear fallout prediction. In Workshop on Satellite Atmospheric Soundings U.S. Army White Sands Proving Ground, 86-97.

The satellite derived product is a wind shear. To obtain the actual winds in the stratosphere, a reference level wind is required: the 15 km wind observed by the radiosonde can be used for this purpose.

The major purpose of this research is to develop and test several methods for retrieving the stratospheric wind shears directly from the satellite observed radiance gradients.

2. Derivation of retrieval methods.

The satellite observed radiance for an observing wavenumber with negligible contribution from the earth's surface may be written as

$$R_i = \int_0^{Z_T} B_i \frac{d\tau_i}{dZ} dZ \tag{1}$$

where i is an index for observing wavenumber, B is the Planck function, τ is the transmittance from the level Z to the top of the radiating atmosphere Z_T, and Z is a measure of the altitude in terms of scale heights

$$Z = -\ln(p/p_o) \tag{2}$$

where p is pressure and the subscript o refers to the surface of the earth.

The horizontal gradient of the observed radiance in the meridional direction is

$$r_i \doteq \frac{\partial R_i}{\partial y} = \int_0^{Z_T} K_i \frac{\partial T}{\partial y} dZ \tag{3}$$

where T is temperature and

$$K_i = \frac{dB_i}{dT} \frac{d\tau_i}{dZ} \tag{4}$$

Equation (3) shows how the horizontal radiance gradient is related to a weighted vertical integral at the horizontal temperature gradient.

The zonal component of the thermal wind in the layer bounded by the levels Z_2 and Z_1 is

$$u_t(Z_2,Z_1) = u(Z_2) - u(Z_1) = -\frac{R}{f}\int_{Z_1}^{Z_2} (\partial T/\partial y)dZ \tag{5}$$

where R is the gas constant and f is the Coriolis parameter. The thermal wind is a good approximation to the actual wind difference between two atmospheric levels as long as the wind field is close to geostrophic, as it generally is above the planetary boundary layer.

Comparison of eqs. (3) and (5) shows that they both contain vertical integrals of the meridional temperature gradient; the difference between the two is that in eq. (3) the integral is over the entire atmosphere and is weighted by K_i whereas in eq. (5) the integral is limited to the layer bounded by Z_2 and Z_1 and is unweighted.

If we define a function $W(Z)$ such that

$$W(Z) = 1 \quad \text{if } Z_1 \leq Z \leq Z_2,$$

$$W(Z) = 0 \quad \text{otherwise},$$

then eq. (5) can be written

$$-\frac{f\, u_t(Z_2,Z_1)}{R} = \int_0^{Z_T} W \frac{\partial T}{\partial y}\, dZ \tag{6}$$

If eq. (3) is multiplied by coefficients c_i and summed over the N observation wavenumbers we obtain

$$\sum_{i=1}^{N} c_i r_i = \int_0^{Z_T} (\sum_{i=1}^{N} c_i K_i)(\partial T/\partial y) dZ \tag{7}$$

Inspection of (6) and (7) indicates that if we approximate W by $\sum_{i=1}^{N} c_i K_i$, then we can estimate the thermal wind from

$$\hat{u}_t(Z_2,Z_1) = -(R/f) \sum_{i=1}^{N} c_i r_i \tag{8}$$

The coefficients c_i can be determined from a procedure that minimizes in some sense the difference between the approximate W-function, which we may denote by $\hat{W}$, and the actual W-function. Fig. 1 shows some actual kernel functions, K_i, and a typical W-function, W..

There are several different ways in which the coefficients c_i can be determined.

a. Method 1.

One way is simply to minimize the form

$$J = \int_0^{Z_T} \left(\sum_{i=1}^{N} c_i K_i - W \right)^2 dz \qquad (9)$$

This procedure would minimize the difference between $\hat{W}$ and W over the entire atmosphere in a least squares sense. The solution to this minimization problem is

$$\underline{c} = \underline{S}^{-1}\, \underline{a} \qquad (10)$$

where

$$S_{ij} = \int_0^{Z_T} K_i K_j \, dZ \qquad (11)$$

and

$$a_i = \int_{Z_1}^{Z_2} K_i \, dZ \qquad (12)$$

With c_i known, u_t can be determined from eq.(8). The meridional component of the thermal wind, v_t, can be obtained with these same c_i by substituting the zonal radiance gradients, $(\partial R_i/\partial x)$, for r_i in (8) and omitting the minus sign.

b. Method 2.

Fleming (1979)[1] (see also Fleming, 1972)[2] has suggested that the coefficients c_i be determined by minimizing the quadratic form

$$J = \int_0^{Z_T} (1-W)^2 \left(\sum_{i=1}^{N} c_i K_i - W \right)^2 dZ \qquad (13)$$

subject to the unit height constraint

$$(Z_2 - Z_1)^{-1} \int_{Z_1}^{Z_2} \left(\sum_{i=1}^{N} c_i K_i \right) dZ = 1$$

Fleming refers to the factor $(1-W)^2$ as a penalty function that tends

1. Fleming, H.E., 1979: Determination of vertical wind shear from linear combinations of satellite radiance gradients: A theoretical study. U.S. Naval Postgraduate School Report NPS63-79-004, 42pp.

2. Fleming, H.E., 1972: A method for calculating atmospheric thicknesses directly from satellite radiation observations. Preprints. Conf. on Atmospheric Radiation, Fort Collins, CO, Amer. Meteor. Soc., 134-137.

to sharpen up the approximate W-function, $\hat{W}$. Since W=1 within the layer (Z_2,Z_1) of interest and W=0 outside of this layer, eq. (13) states that the integral of $\hat{W}$ outside the layer of interest should have a mininum value. The unit height constraint insures that the integral of $\hat{W}$ is equal to the integral of W within the layer of interest. The solution to this minimization problem is

$$\underline{c} = \frac{\ell\, \underline{S}^{-1}\, \underline{a}}{\underline{a}^T\, \underline{S}^{-1}\, \underline{a}} \tag{14}$$

where

$$S_{ij} = \int_0^{Z_1} K_i K_j dZ + \int_{Z_2}^{Z_T} K_i K_j dZ \tag{15}$$

and $\ell = Z_2 - Z_1$.

c. Method 3

To determine whether there is any significant difference between the simple minimization of method 1 and the use of the penalty function as in method 2, we may use method 1 with the same unit height constraint as in method 2. Formally, the solution is the same as for method 2, i.e. eq. (14), but with S_{ij} defined as in method 1, i.e. eq. (11).

d. Method 4.

Methods 2 and 3 both use the unit height constraint. This insures that areas such as those labelled C in figure 2 would cancel each other. However, the excess areas labelled A and B are undesirable and lead to inaccuracies in the solution. Fleming (1972)[2] suggests compensating for these areas by multiplying the solution of method 2 by the factor

$$f = \ell / \int_0^{Z_T} \hat{W} dZ \tag{16}$$

e. Method 5.

To insure that the correct solution is obtained in the case where the thermal wind is not a function of altitude, i.e., the horizontal temperature gradient is constant with altitude, we may proceed as follows. Combine (5), (6) and (8) to obtain

$$\widehat{\int_{Z_1}^{Z_2} (\partial T/\partial y) dZ} = \sum_{i=1}^{N} c_i r_i = \int_0^{Z_T} \left(\sum_{i=1}^{N} c_i K_i \right) (\partial T/\partial y) dZ \tag{17}$$

where the caret, as before, indicates the estimated value. For $(\partial T/\partial y)$ constant with altitude,

$$\widehat{(\partial T/\partial y)}(Z_2-Z_1) = (\partial T/\partial y) \int_0^{Z_T} (\sum_{i=1}^{N} c_i K_i) dZ \tag{18}$$

From (18) it can be seen that the estimated temperature gradient $\widehat{\partial T/\partial y}$, will equal the actual temperature gradient if

$$(Z_2-Z_1)^{-1} \int_0^{Z_T} (\sum_{i=1}^{N} c_i K_i) dZ = 1 \tag{19}$$

This is a different form of the unit height constraint. Eq. (19) can be interpreted as stating that the vertical integral of the approximate W-function should be equal to the vertical integral of the exact W-function. This seems to be a more appropriate normalization constraint than the one given in method 2. The use of this constraint with the minimization of eq. (9) constitutes method 5. The solution is

$$\underline{c} = \underline{S}^{-1}\underline{a} + \frac{\ell - \underline{b}^T \underline{S}^{-1} \underline{a}}{\underline{b}^T \underline{S}^{-1} \underline{b}} \underline{S}^{-1} \underline{b} \tag{20}$$

where

$$b_i = \int_0^{Z_T} K_i dZ \tag{21}$$

f. Traditional and regression methods.

The above five methods may be called direct retrieval methods since the thermal winds are obtained directly from the radiance gradients. Using a set of colocated radiance and radiosonde data, we shall compare the results obtained from the different direct methods. We shall also compare the results of the direct methods with results obtained from method T, the traditional method, in which the thermal wind is computed from the temperatures retrieved from radiance observations, and from a linear regression method based on the relationship between the observed wind shears and the observed radiance gradients. The results obtained from the regression method represent a limiting accuracy for a particular data set for any direct linear method.

3. Experimental details.

A special series of 31 concurrent (within 1 hour) sets of radiance observations from the NOAA-4 VTPR instrument and wind shear from radiosonde observations, distributed throughout one year (Feb. to Dec. 75), for the White Sands Missile Range area in New Mexico (see Fig. 3), is used for evaluating the different methods. The horizontal radiance gradients over this area are estimated from a 7 x 7 slightly rectangular array of satellite radiance observations extending over an area of about 500 km on the side. The spot size (50% power contour) of each radiance observation ranges from 60 km at the sub-satellite point to about 80 km at the end of each scan line. To compute the radiance gradients, four averages of 3 x 7 grid points each, as shown in Fig. 3, were made of the radiances and of the location coordinates. The radiance gradients are then obtained from application of the Taylor approximation formulas to these average values

$$\Delta R_1 = \overline{R}_A - \overline{R}_B = \frac{\partial R}{\partial x} \Delta x_1 + \frac{\partial R}{\partial y} \Delta y_1 \tag{22}$$

$$\Delta R_2 = \overline{R}_c - \overline{R}_d = \frac{\partial R}{\partial x} \Delta x_2 + \frac{\partial R}{\partial y} \Delta y_2 \tag{23}$$

where $\overline{R}_A$, $\overline{R}_B$, $\overline{R}_C$ and $\overline{R}_D$ are the average radiances (at a particular wavenumber) for the regions A, B, C and D, as shown in Figs. 3 and 4, and Δx_1, Δy_1, Δx_2 and Δy_2 are shown geometrically in Fig. 4. These two simultaneous equations can be readily solved for the unknown radiance gradients $\partial R/\partial x$ and $\partial R/\partial y$. This simple method gave approximately the same results as a planar fit by a regression technique.

"Ground truth" was obtained from radiosonde balloons launched (nearly) simultaneously from the three stations shown in Fig. 3 about one hour prior to the overpass of the NOAA-4 satellite. The average of the three measured wind profiles was used as "truth" data for the different methods.

It was decided to compare the direct methods using just the three upper atmosphere channels (695.5, 679.5, 667.8 cm^{-1}). Sample comparisons with the use of four channels indicated no improvement in the results.

The atmospheric transmission for each of CO_2 band observing channels is assumed to be a product of the CO_2, H_2O and O_3 transmissions in that channel. A zenith angle correction to the transmissions is also included. These transmissions are computed for each case from a

first guess temperature and water vapor profile and from a standard ozone distribution.

In the traditional method, temperature retrievals are obtained with an inversion scheme similar to that of Hogan and Grossman (1972).

4. Results

Before discussing the results, it is instructive to compare the approximate W-functions of the different direct methods. Fig. 5 shows the $\hat{W}$-function for the five direct methods for the layer 125-25 mb. The $\hat{W}$-functions of methods 2 and 3 are almost identical. This suggests that there is no particular advantage to be gained by using the penalty function as in eq. (13) rather than a straightforward minimization technique. It will be recalled that methods 2 and 3 both use the unit height constraint applied to the layer of interest. While this insures that, within the layer of interest, the area under $\hat{W}$ is equal to the area under W, it also causes greater side lobes outside the layer of interest than those of the other methods. Although method 4 also makes use of the unit height constraint in the layer of interest, the final solution coefficients are reduced by a common factor in order to reduce the side lobes, thus nullifying the intent of of the unit height constraint. The $\hat{W}$ functions of the other layers have similar characteristics.

Just as the $\hat{W}$-functions of the different methods group themselves into two distinct groups - those <u>with</u> unit height constraint within the layer of interest and those <u>without</u> (included here is method 4) - so do the results. There were no substantial differences in the

results obtained with methods 2 and 3, and there were no substantial differences in the results obtained with methods 1, 4 and 5. Therefore, in the discussion that follows the results of method 1 are used to represent methods 1, 4 and 5, which we may call group 1, and the results of method 2 are used to represent methods 2 and 3, which we may call group 2.

Table 1 compares the arithmetic (or systematic) errors of the group 1 and group 2 direct methods and the traditional (T) method. Also shown in the table are the observed mean wind shears. The wind shears represent the change in wind speed from the base to the top of each layer.

In general, the group 2 methods have a much greater systematic error than the group 1 methods, especially for the u-component of the wind shear. The arithmetic errors of group 1 are, in general, somewhat less than those of the traditional method. The arithmetic errors of group 1 and the traditional method are small compared to the observed mean u-component wind shears, but are of the same size as the observed v-component shears, which are of the order of 1 m s^{-1} for each layer.

Table 2 shows a comparison of the root-mean-square errors of the various methods. Also included in this table are the standard

errors (S.E.) of a linear regression method based on the relationship between the observed wind shears and observed radiance gradients. These standard errors represent estimates of the minimum root-mean-square-errors that can be achieved by any direct linear retrieval method. In addition, the table includes the standard deviations (σ) of the observed wind shears.

Inspection of Table 2 reveals that the root-mean-square-errors of group 2 are typically more than twice as large as those of group 1, the mean root-mean-square-errors for the four layers between 250 and 10 mb being 2.1 m s^{-1} and 3 m s^{-1}, respectively, for the u-component, and 7.5 and 15.5 m s^{-1} for the v-component.

A comparison of group 1 root-mean-square-errors with those of the traditional method shows that they are about the same magnitude for u-component but greater for group 1 for the v-component. However, for neither method does the root-mean-square-error go much below the standard deviation of the observations. This implies that the error obtained by assuming that the wind shear is always equal to the observed climatological value at White Sands would be no greater than that obtained when satellite observations are used to estimate the wind shears.

Comparison of the root-mean-square-errors of the direct methods and the standard errors of the regression technique shows that the difference between the two is larger for the v-component of the wind shear than for the u-component.

In both Tables 1 and 2, a separate row of results is presented for the 125-25 mb layer. This layer is approximately twice as large as the other layers, and it was thought that, in view of the "resolving power" difficulties of the basic radiance observations, the results might be improved for such a "thick" layer. However, inspection of the tables indicates that there is no particular reduction in the errors for this thicker layer.

5. Conclusions and discussion.

Several methods have been derived for determination of thermal winds directly from the horizontal gradients of satellite radiance observations. These methods are intercompared using a special series of satellite VTPR radiance and radiosonde wind observations over the White Sands Proving Ground area in the United States. The direct methods are also compared to the "traditional" method, in which thermal winds are computed from the horizontal temperature gradients obtained from temperature profiles retrieved from the satellite radiance observations, and to a linear regression method.

Of the direct methods tested, those that do not apply the unit height constraint to the layer of interest give the best results. The use of the unit height constraint causes larger side lobes in the $\hat{W}$-function, thus introducing more undesirable information from the region outside the layer of interest than in the case of the methods that have no such constraint.

There appears to be no particular advantage to introducing a penalty function $(1-W)^2$, into the integral form that is minimized to obtain the solution coefficients for the direct methods.

The best direct methods gave results comparable to those obtained with the traditional method. However, all the methods examined are not particularly skillful at retrieving the wind shears from the radiance observations. This lack of skill is probably associated with a number of factors.

We believe that the major factor leading to lack of skill is the error associated with trying to evaluate a relatively small horizontal gradient over a relatively small horizontal distance. For the geographical region and atmospheric layers studied in this research, typical u-component wind shears are of the order of 10 m s^{-1}. Such wind shears imply, through the thermal wind equation, meridional temperature gradients of about 3.5^{o}C per 1000 km. Differentiation of the Planck function with respect to temperature indicates that, for the temperatures and wavenumbers of concern here, a change of 1^{o}C is equivalent to a change of one radiance unit (mW/m^2 sr cm^{-1}). Thus, the observed wind shears are associated with radiance gradients that are of the order of 3.5 radiance units for 1000 km. However, in the present investigation these radiance gradients are estimated from radiance observations over characteristic horizontal distances of about 300 km - which means radiance differences of about 1 radiance unit or temperature differences of about 1^{o}C must be measured.

The VTPR instruments had characteristic sensitivities of 0.25 radiance units (even larger at 667.8 cm^{-1}), a significant fraction of the radiance differences that had to be measured in order to retrieve the observed thermal winds. Thus, the VTPR instruments are just not sensitive enough to measure the small horizontal radiance differences over distances of ~ 300 km associated with typical meridional temperature gradients in the stratosphere over White Sands. The situation for the v-component is even worse, since typical v-component wind shears are less than those of the u-component.

Other factors contributing to errors in the retrievals include the differences between the actual and the approximate W-functions, uncertainties in transmission functions, and possible differences between the thermal wind shear and the actual wind shear.

The above discussion leads us to suggest that much better results might be obtained by applying the direct methods of the group 1 type to regions of the atmosphere with typically greater wind shears than those encountered in the stratosphere over White Sands and/or to characteristic horizontal distances greater than the 300 km used in the present study. Improved instrumentation in the current generation of satellite sounding equipment should also lead to improved retrievals.

Acknowledgement.

The research reported herein has been sponsored in part by the United States Army through its European Research Office.

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Hogan, J.S., and Grossman, K., 1972: Tests of a procedure for inserting satellite radiance measurements into a numerical circulation model. J. Atmos. Sci., 29, 797-800.

Appendix

1. List of publications resulting from research performed under this and preceding Grant.

Ohring, G., and Goldberg, D., 1977: A direct method for obtaining ballistic densities from satellite radiance observations. J. Appl. Meteor, 16, 855-858.

Ohring, G., and Neeman, B., 1980: Comparison of some methods for determination of thermal winds from satellite radiance observations. Extended Abstracts Volume, International Radiation Symposium, Fort Collins, CO., 70-72.

Ohring, G., Neeman, B. and Duncan, L.D., 1980: Direct determination of wind shears from the gradients of satellite radiance observations. To be submitted to J. Appl. Meteor.

Ohring, G., 1979: Impact of satellite temperature soundings on weather forecasts. Bull. Amer. Meteor. Soc., 60, 1142-1147.

2. List of students who have received support from this and preceding Grants.

Student	Degree	Year
Dina Goldberg	M.Sc.	1976
Eliram Broida	M.Sc.	1978
Binyamin Neeman	Ph.D student	

Figure Captions

Fig. 1 K_i and W functions.

Fig. 2 Schematic W and W functions.

Fig. 3 Typical array of satellite radiance observation points over the White Sands area. Each dot represents the center of a spot observed by the satellite. The circled crosses show the locations of the radiosonde stations that were used for "ground truth". The rectangles A,B,C and D are used in the computation of radiance gradients as explained in the text (see also fig. 4).

Fig. 4 Schematic diagram showing how observations from areas A,B,C and D are used to compute radiance gradients. See text.

Fig. 5 Comparison of approximate ($\hat{W}$) and actual W functions for 125-25 mb layer.

Table 1. Mean observed wind shears and mean arithmetic errors of wind shear retrievals ($m\ s^{-1}$).
Method 1 represents the group of methods 1, 4 and 5;
Method 2 represents the group of methods 2 and 3; and
N is the number of comparisons.

Layer		u-component				v-component				
			Method				Method			
(mb)	(km)	Observed	1	2	T	Observed	1	2	T	N
250-100	10.4-16.2	-8.2	6.9	7.7	2.4*	-0.4	0.7	1.0	0.0*	31
100-50	16.2-20.6	-11.6	1.9	-7.4	5.8	-1.0	0.5	0.4	1.1	31
50-20	20.6-26.5	-4.0	-1.7	-9.8	-1.6	-0.3	-0.2	-1.0	0.7	28
20-10	26.5-31.1	1.2	-0.2	4.1	-3.4	1.1	-0.7	-0.9	-0.7	15
125-25	14.8-25.0	-19.8	3.4	-1.9	7.9	-2.1	1.3	1.0	2.3	31

* Values for Method T are for the 300-100 mb layer (9.6-16.2 km).

Table 2. Root-mean-square-errors, standard error of regression technique (S.E.), and standard deviation of observations of wind shear (σ) (m s^{-1}). Method 1 represents the group of methods 1, 4 and 5; Method 2 represents the group of methods 2 and 3, and N is the number of comparisons.

Layer		u-component					v-component					N
		Method					Method					
(mb)	(km)	1	2	T	S.E	σ	1	2	T	S.E	σ	
250-100	10.4-16.2	12.	14	7.6*	7.7	10.1	11.	14	8.3*	7.3	11.7	31
100-50	16.2-20.6	6.8	14	7.9	4.9	5.0	6.5	11	3.5	3.5	4.7	31
50-20	20.6-26.5	8.0	22	5.2	5.5	7.0	8.0	18	4.4	3.5	3.5	28
20-10	26.5-31.1	5.8	35	6.3	4.9	7.3	4.5	19	2.5	2.4	2.1	15
Mean		8.9	21	6.7	6.5	7.9	8.4	19	4.7	4.4	6.0	
125-25	14.8-25.0	8.7	10	10.1	6.4	9.4	12.	15	5.5	5.5	8.0	31

* Values for Method T are for the 300-100 mb layer (9.6-16.2 km)

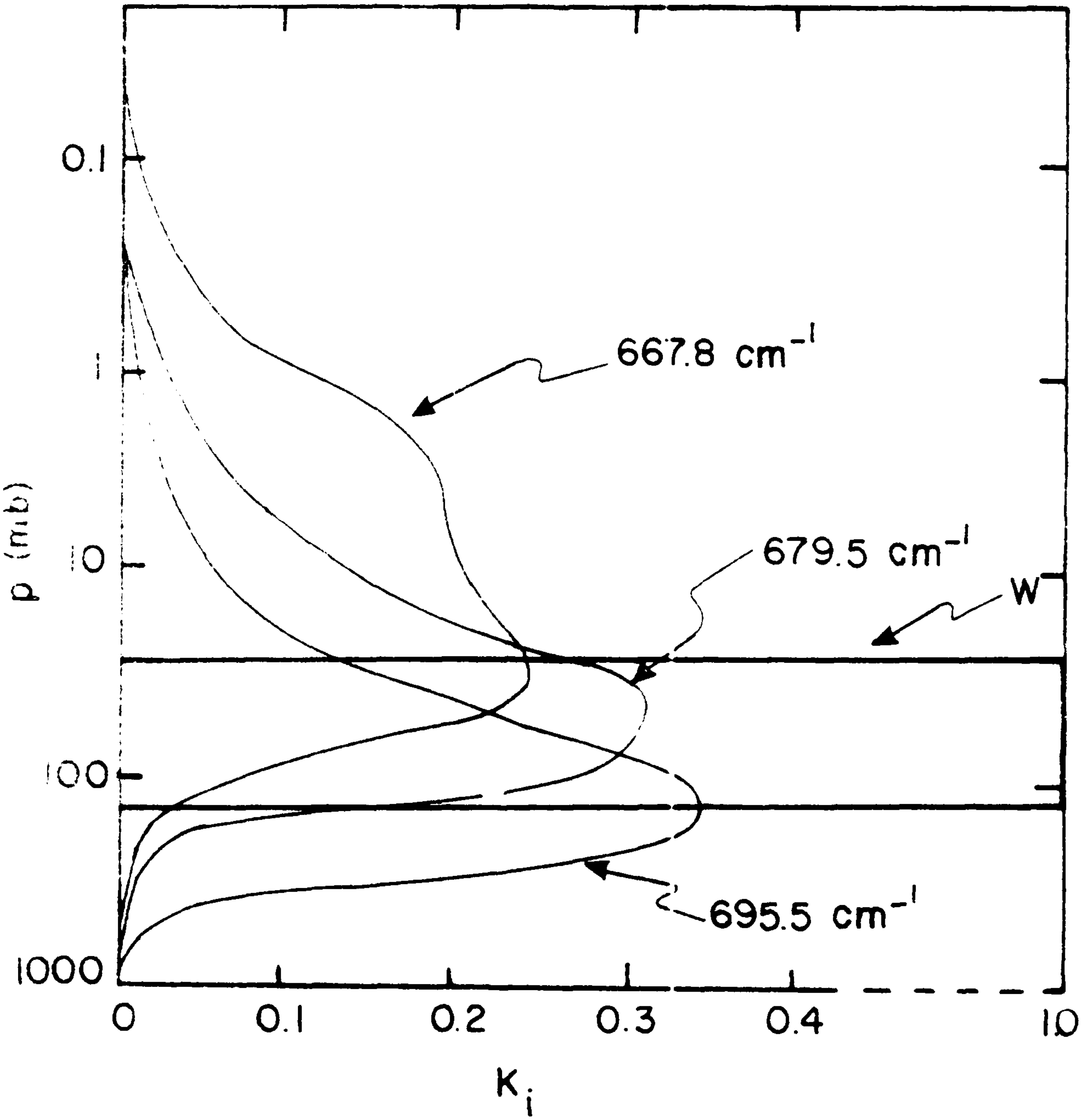


Fig. 1 K_i and W functions.

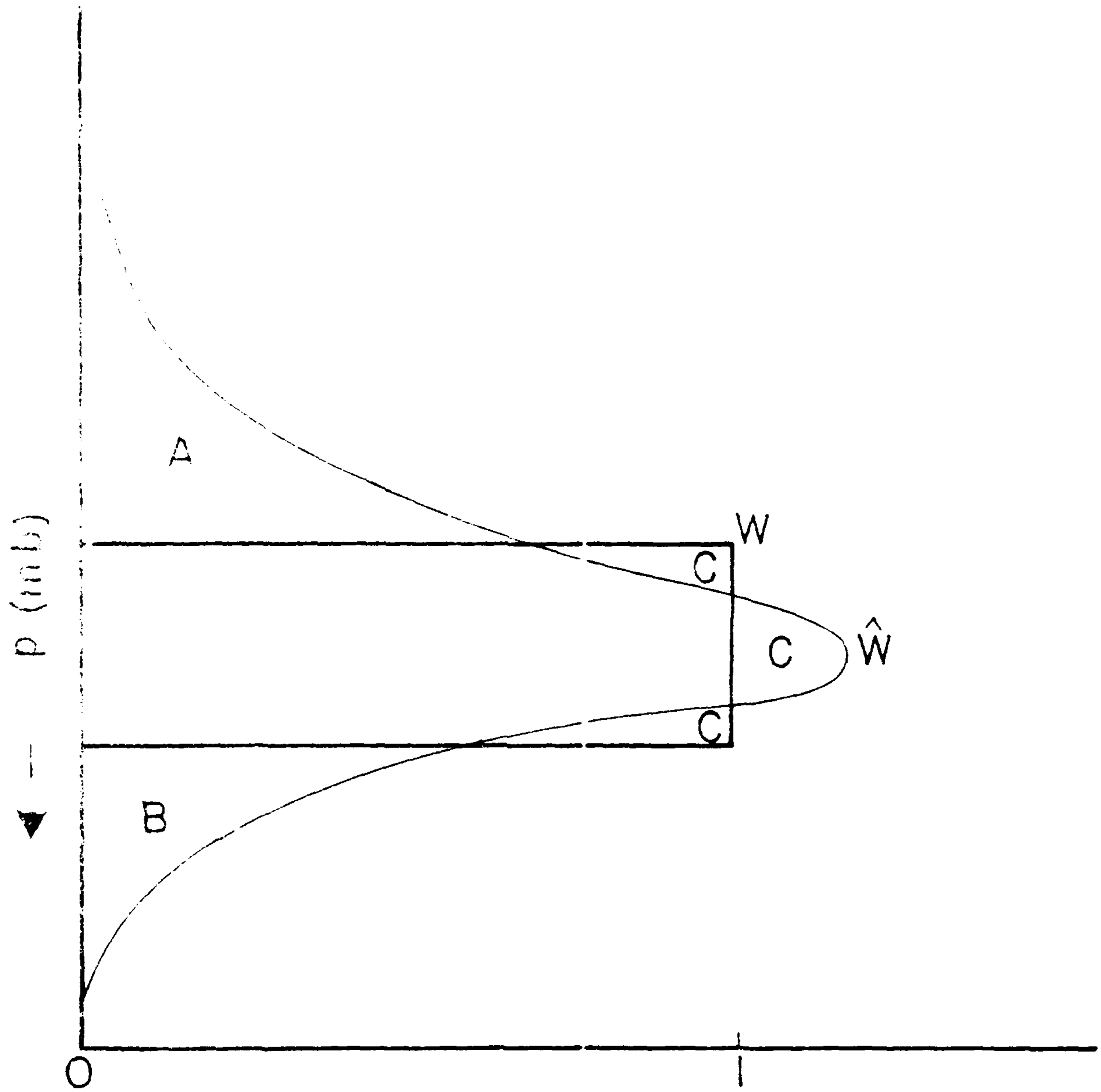


Fig. 9 Schematic W and Ŵ functions.

Fig. 3 Typical array of satellite radiance observation points over the White Sands area. Each dot represents the center of a spot observed by the satellite. The circled crosses show the locations of the radiosonde stations that were used for ''ground truth''. The rectangles A,B,C,and D are used in the computation of radiance gradients, as explained in the text (see also fig. 4).

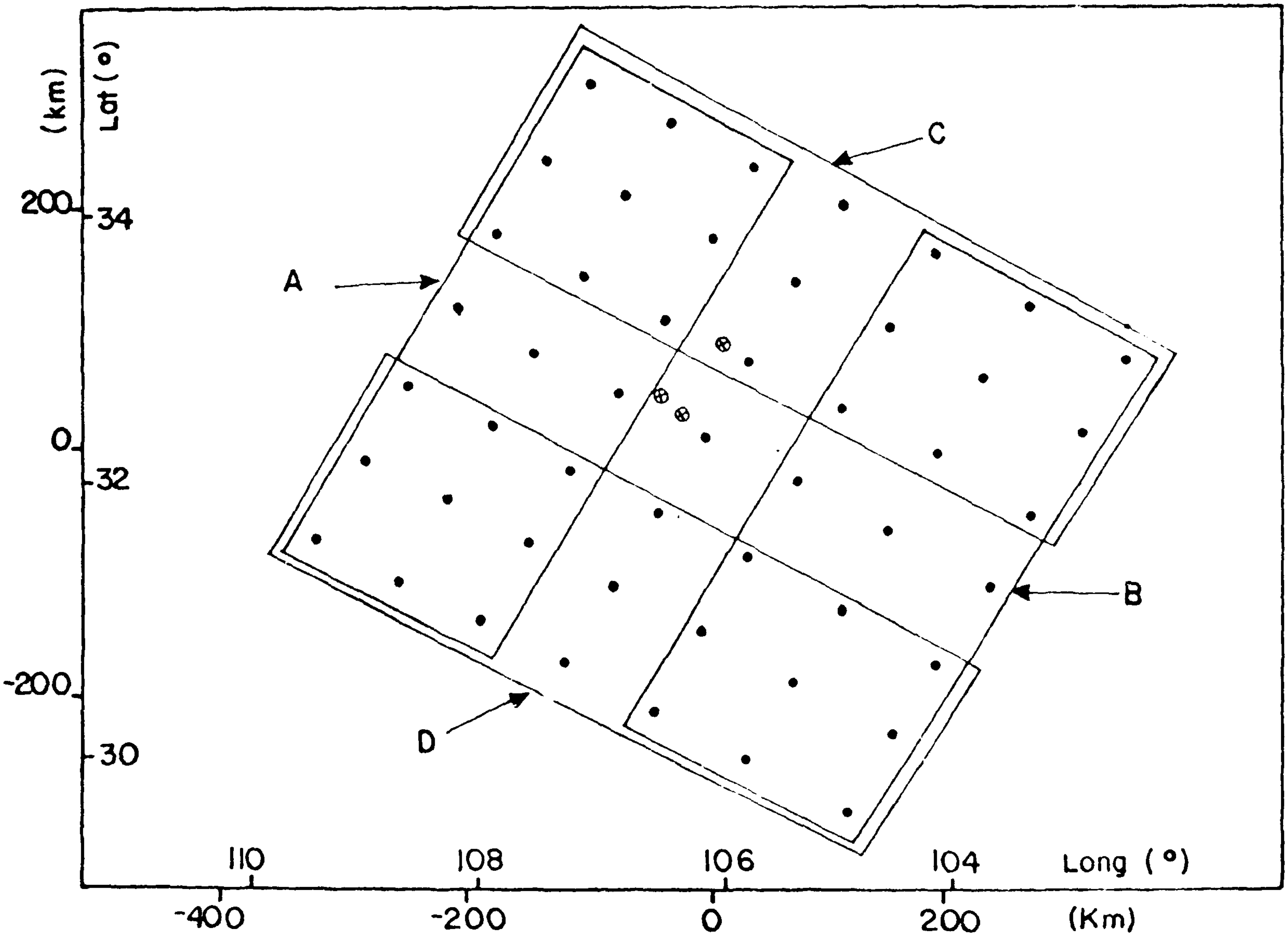
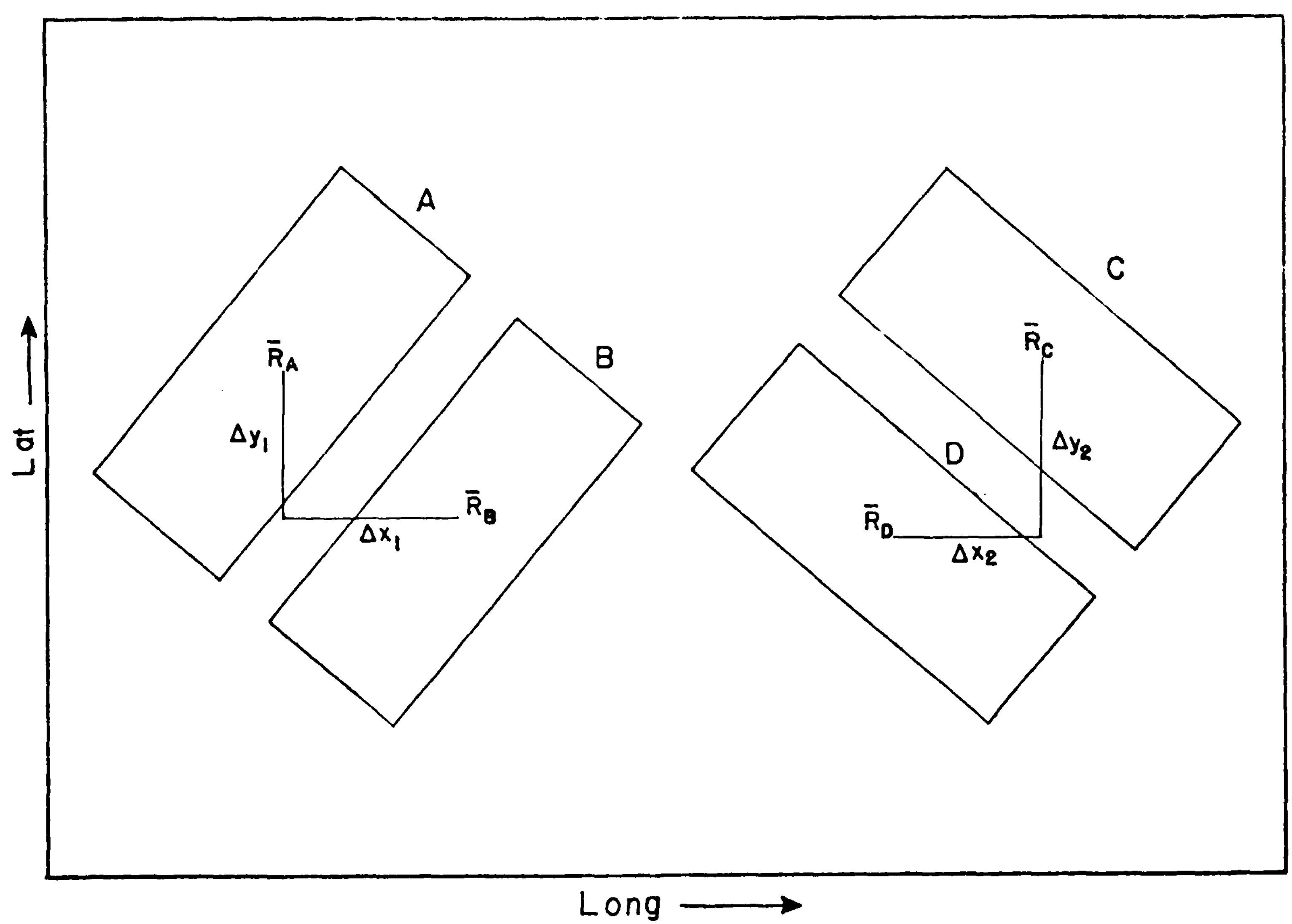


Fig. 4 Schematic diagram showing how observations from areas A,B,C and D are used to compute radiance gradients. See text.



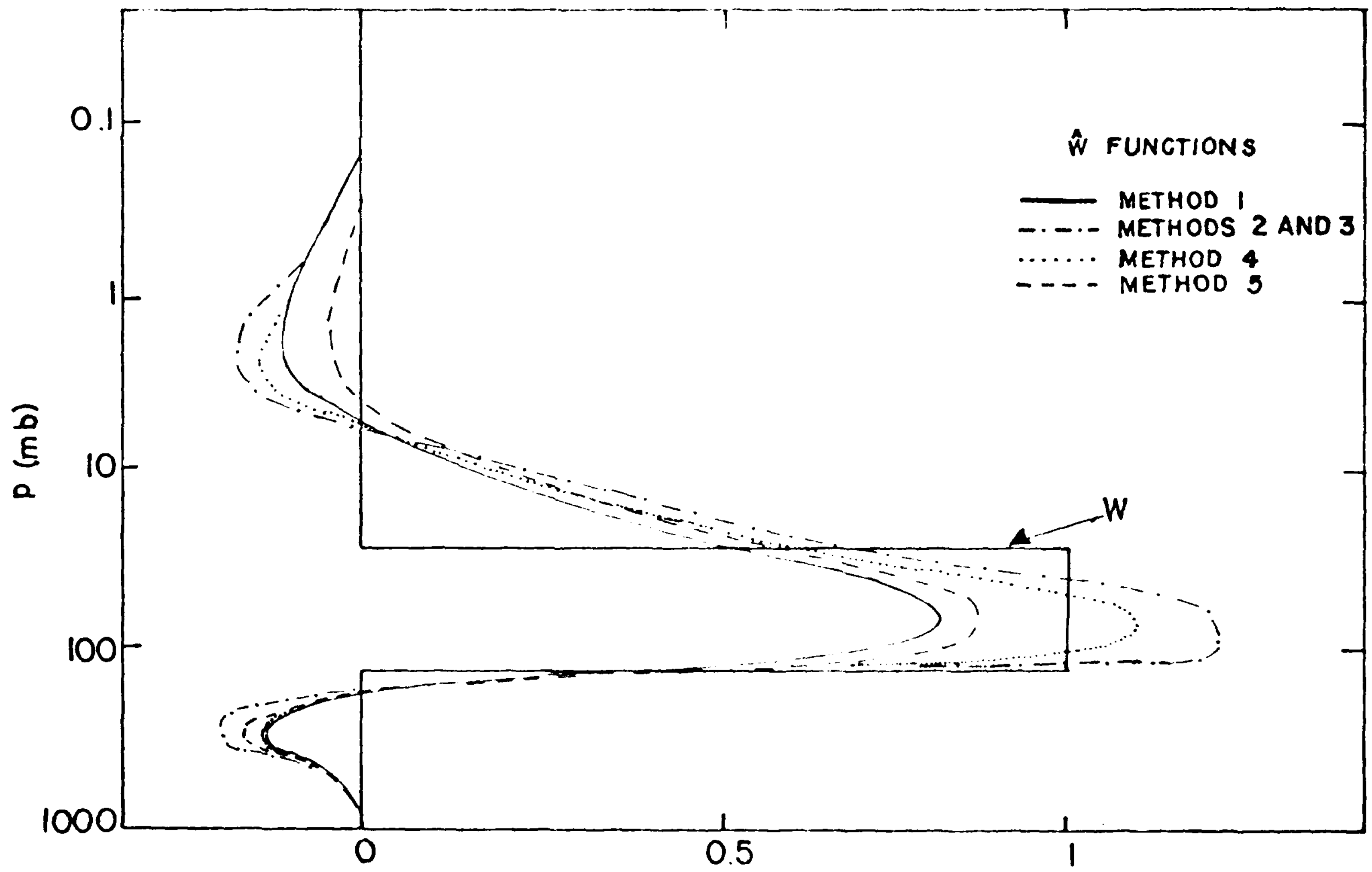


Fig. 5 Comparison of approximate ($\hat{W}$) and actual W functions for 125-25 mb layer.

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Impact of Satellite Temperature Sounding Data on Weather Forecasts[1]

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Abstract

The concept of radiometric sounding of atmospheric temperature profiles from satellites was first demonstrated with data gathered by infrared spectrometers on the Nimbus-3 satellite in 1969. Operational satellite sounding over oceanic areas was introduced by the VTPR (Vertical Temperature Profile Radiometer) instrument on the NOAA 2 satellite in 1972. Early evaluations of these new observational data centered on their accuracy compared to data obtained from the conventional radiosonde system. More recent evaluations have focused on the impact of the satellite temperature soundings on numerical weather forecasts. In this paper, we review the results of such impact tests in several countries. On the average, the inclusion of satellite sounding data leads to a small improvement in the numerical forecasts.

1. Introduction

The VTPR instrument on the operational U.S. weather satellites provided about 1000 sounding temperature profiles per day over the oceans of the globe. This number is about one half of the total number of radiosonde reports available daily. The VTPR temperature profiles, processed in Washington, D.C., were available over the global meteorological telecommunications circuit. The infrared and microwave sounding systems on the U.S. experimental satellite Nimbus-6 (prototypes of the sounding system for the operational satellite TIROS-N), were capable of providing about 5000 temperature soundings daily, over land and water. Satellite temperature soundings are in the form of temperature versus pressure and can be converted to thicknesses directly or to geopotential heights with the use of the hypsometric equation and a knowledge of the height of some reference level, generally the 1000 mb surface. Satellite data are asynoptic; they can be included in the analysis for a particular observing time either by means of an observing window (e.g., the use of data ±3 hours around the observing time) or an asynoptic assimilation scheme. Most evaluations of the impact of satellite soundings on forecasts are made by running two parallel sets of forecasts, one set based on initial analyses that do not include satellite temperature sounding data, the other on initial analyses that include these data. The two sets of forecasts are then verified against the observed states of the atmosphere, generally in regions with dense radiosonde networks.

A number of such impact tests have been performed by various groups around the world. The results have been published in scientific journals or in reports. We have attempted to collect the results of these studies for presentation here. As part of this attempt, we have written to a number of national meteorological services requesting any information they could provide on the impact of satellite soundings on forecasts. Part of the information provided was qualitative in nature. We summarize in the next section both the quantitative and qualitative information we have compiled.

2. Results

a. *Quantitative impact*

Impact evaluation tests have been performed by a number of groups, using different analysis, forecasting, and verification methods. We have chosen the 48 h 500 mb geopotential height forecast for evaluating the impact of satellite sounding data. This particular forecast was chosen because it represents an important atmospheric level and forecast range, and results for this forecast were available from almost all of the impact studies. The most popular forecast verification criteria were the rms errors and S1 skill score. We shall present the impact results in terms of one or the other (or both, where available) of these criteria. The S1 score is given by

$$100 \sum |e_G| \big/ \sum |G_L|$$

where e_G is the error of the forecast height difference and G_L is the observed or forecast height difference between grid points, whichever is larger. The lower the score, the more skilful the forecast. Twenty years of

[1] Expanded version of paper presented at the COSPAR Symposium on the Remote Sounding of the Atmosphere from Space, Innsbruck, Austria, 1–3 June, 1978.

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TABLE 1. Impact of satellite soundings on rms errors of 48 h 500 mb geopotential height forecasts (m). (Positive impact represents reduction in rms height error.)

Source	Verification area	Season	Data	Number of forecasts	NOSAT	SAT	Impact
Desmarais *et al.* (1978)	Eastern N. America	Summer	V + N	10	45.8	47.9	−2.1
	Western N. America				43.5	45.0	−1.5
	N. America	Winter	V + N	15	65.0	63.7	1.3
Halem *et al.* (1978)	N. America	Winter	V + N	11	77.9	72.8	5.1
Bonner *et al.* (1976)	N. America	Spring	V	9	63.4	60.6	2.8
Atkins and Jones (1975)	Europe, Atlantic, Canada, NE USA	Spring	V	7	94.0	88.0	6.0
Druyan *et al.* (1978)	Europe, Mid-East, N. Africa						
	Experimental VTPR	Winter	V	26	70.0	67.0	3.0
	Operational VTPR	Winter	V	13	69.3	67.3	2.0
Kelly (1977)*	Australia	Winter	V	9	49.0	43.6	5.4

V = VTPR soundings, N = Nimbus-6 soundings.
* 36 h forecasts.

experience in the use of S1 scores at the U.S. National Meteorological Center (NMC) indicates that the practical range between a perfect and worthless forecast at 500 mb is 20–70 (Fawcett, 1977).

Table 1 shows the impact of satellite sounding data on numerical forecasts as measured by the reduction in rms geopotential height errors, a positive impact representing a reduction in the error when satellite sounding data are included. NOSAT refers to the rms error when no satellite soundings are included in the initial analyses and SAT refers to those cases in which satellite soundings were added to the data base of the initial analyses. Except for the summer results of Desmarais *et al.* (1978) the impacts are all positive, indicating improved forecasts when satellite sounding data are included. However, the impacts are all small, ranging from 3–6 m, while the error levels of the forecasts are in the range of 45–100 m. The largest improvement, percentagewise, is obtained in the Southern Hemisphere (Kelly, 1977) where the impact is greater than 10%. In all studies, the small average impact obtained is the result of a combination of positively influenced and negatively influenced forecasts and not the result of a consistent impact on each forecast.

Table 2 shows impact results in terms of S1 skill scores, a positive impact meaning a reduction in the S1 score when satellite sounding data are included; a reduction in S1 represents an improvement in the forecast. The S1 results confirm the rms error results. Small positive impacts are obtained in all studies, except for the tiny negative impact in the summer results of Desmarais *et al.* (1978). The most impressive results are once again in a Southern Hemisphere study where a reduction of almost 5 points is registered in the S1 score when satellite soundings are included (Kelly *et al.*, 1978). Once again each impact listed consists of the mean of a set of forecasts, some of which showed positive impact and some of which showed negative impact.

It is of interest to compare the winter results of Desmarais *et al.* (1978) at NMC with those of Halem *et al.* (1978) at GISS (Goddard Institute for Space Studies). Ten of the forecasts were common to both studies. The NMC obtained a positive impact of 0.5 points in S1 score, representing a reduction of S1 from 34.8 to 34.3. GISS obtained a positive impact of 1.9 points in S1, representing a reduction from 39.6 to 37.7. Halem *et al.* (1978) imply that GISS's greater positive impact is the result of a better assimilation and analysis

TABLE 2. Impact of satellite soundings on S1 scores of 48 h geopotential height forecasts. (Positive impact represents reduction in S1, improvement in forecast.)

Source	Verification area	Season	Data	Number of forecasts	NOSAT	SAT	Impact
Desmarais *et al.* (1978)	N. America	Summer	V + N	10	46.0	46.1	−0.1
		Winter	V + N	15	34.8	34.3	0.5
Halem *et al.* (1978)	N. America	Winter	V + N	11	39.6	37.7	1.9
Bonner *et al.* (1976)	N. America	Spring	V	9	44.2	45.6	1.4
Kelly (1977)*	Australia	Winter	V	9	42.0	40.0	2.0
Kelly *et al.* (1978)**	Australia	Winter	N	28	42.2	37.4	4.8

V = VTPR soundings, N = Nimbus 6 soundings.
* 36 h forecasts.
** 24 h forecasts.

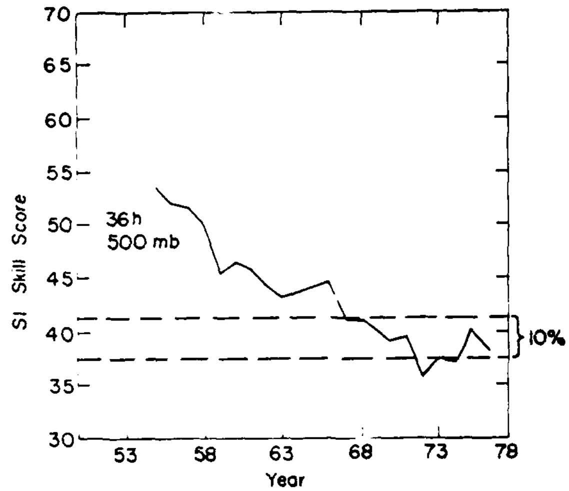

FIG. 1. Mean annual S1 skill score of NMC's 36 h forecasts at 500 mb during the period 1955 76. (From Halem *et al.*, *1978; extension of data presented by Fawcett, 1977.*)

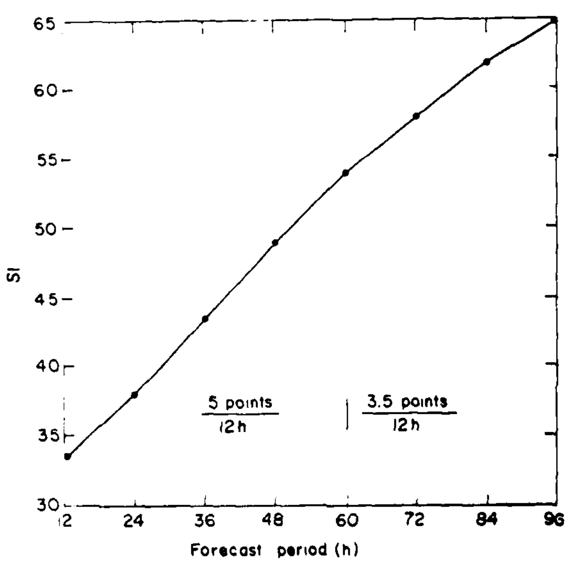

FIG. 2. S1 skill score of NMC six-level primitive equation model at 500 mb as a function of forecast period. (*After* Desmarais *et al.*, 1978.)

scheme. Desmarais *et al.* (1978) suggest that the greater impact registered by GISS is simply due to more room for improvement in GISS's analysis and forecast system, as evidenced by better (by 5 points) NOSAT S1 scores of NMC's forecasts. (That the difference in S1 scores is not due to different areas or grid intervals in the two studies is shown by Desmarais *et al.* (1978) who used exactly the same verification code for evaluating GISS and NMC S1 scores, and found the same ~5 S1 point difference.) In particular, Desmarais *et al.* (1978) imply that GISS's analyses without satellite soundings are poorer than NMC's and, therefore, the addition of satellite soundings can improve GISS's analyses more than they can improve NMC's analyses; hence, a greater impact in GISS's forecasts. To help resolve this question, it would be desirable to apply GISS's assimilation and analysis scheme to the NMC forecast model in a series of impact tests. Experiments along these lines are currently underway (Ghil *et al.*, 1979a).

The question naturally arises as to the meaning or significance of a small improvement, say 1 or 2 points, in the S1 skill score at 500 mb. Some light can be shed on this question by Figs. 1 and 2. Figure 1 shows the mean annual S1 score of the NMC's 36 h forecasts at 500 mb during the period 1955-76 (from Halem *et al.*, 1978; extension of data presented by Fawcett, 1977). A general trend toward lower S1 scores, i.e., improved forecasts, can be seen during the period. Over the last 10 years there has been about a 10% improvement in the S1 score, i.e., a reduction of about 4 points. If this rate can also be assumed representative of the 48 h forecast, then a reduction of 1 or 2 points in the S1 score represents an improvement that currently takes about 2 to 5 years to achieve. Figure 2 (after Desmarais *et al.*, 1978) shows the 500 mb S1 score of the NMC 6-level primitive equation model as a function of forecast period. For forecast periods less than 60 h, the forecast deteriorates at a rate of about 5 S1 points for 12 h. Thus, an improvement of 1 or 2 points in the S1 score is equivalent to an extension of forecast capability by about $2\frac{1}{2}$-5 h at the 48 h forecast range.

A 1 or 2 point S1 impact may be small compared to the differences in the performance of differing analysis and forecasting systems, e.g., GISS versus NMC. Operational experience at NMC (Shuman, 1978) has shown step jumps greater than 1 or 2 points when improved models are adopted (e.g., after introduction of the 6-level primitive equation model, or the fine mesh model). But improvements in the forecast models may be more difficult to achieve today than in the past (there is less room for improvement) and a 1 or 2 point improvement in S1 score may be significant at today's state of model development.

In all the studies, as previously noted, the small average impact obtained is the result of a combination of positively influenced and negatively influenced forecasts and not the result of a consistent impact on each forecast. This is illustrated (Fig. 3) by a breakdown of the impacts registered by Halem *et al.* (1978) for North America during a winter period. Although the average impact was positive, representing a reduction of 1.9 points in skill score, in 3 out of the 11 forecasts the impact was negative.

b. Qualitative impact

Qualitative information on the impact of satellite soundings on numerical weather forecasts was obtained

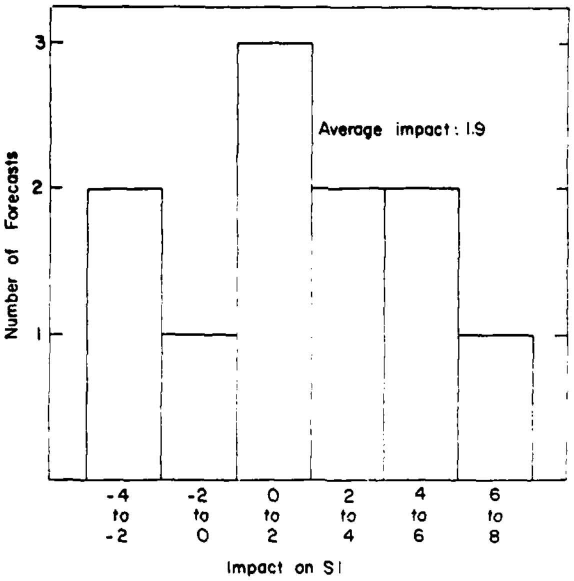

FIG. 3. Histogram of impacts of satellite sounding data on 48 h 500 mb S1 scores for North America during a winter period. (After Halem *et al.*, 1978.)

from several national meteorological services. Their findings are summarized below.

Weather Bureau, Republic of South Africa The 1000–300 mb thickness field is one of two primary fields predicted, and both satellite sounding data and satellite-derived winds are included in the operational manual analyses of this field. The Weather Bureau, Republic of South Africa, indicates that "although we have, as yet, made no objective assessment of the impact of satellite sounding data and cloud imagery on the quality of our numerical analyses and numerical prognoses, we are convinced that it must be considerable" (Triegaardt, 1978, private communication).

Meteorological Service, France. The experience of the French Meteorological Service indicates that if one removes the satellite sounding data from the initial conditions of a particular forecast, the resulting forecast is not significantly different from a forecast based on initial conditions including the satellite data (Mittner, 1978, private communication). However, if one removes the satellite soundings from the operational objective analysis scheme for a period of several consecutive days, one observes a progressive degradation of the analyses and the forecasts, particularly in those areas not well covered by other types of observations.

Meteorological Service, Federal Republic of Germany. The FRG Meteorological Service indicates that satellite sounding data are used routinely in the numerical analysis procedure. Although no impact experiments have been performed, "we feel that the old system with eight weather ships in the Atlantic Ocean provided more valuable information about actual weather phenomena which cannot be replaced by currently available satellite soundings" (Buschner, 1978, private communication).

3. Discussion and conclusions

Our survey of the impact of satellite soundings on numerical forecasts indicates that current satellite data as used in current analysis and forecast models produce, on average, a small improvement in the numerical forecasts. (It should be noted that the Nimbus-6 soundings were never used operationally but only in simulations of operational forecasts). However, this small average positive impact is not based on consistent small positive impacts in each forecast, but rather on an average of forecasts with positive impact, negative impact and no impact. The small effect of the satellite data is also evidenced by almost all qualitative and synoptic evaluations of their impact. Subjective evaluations of NOSAT and SAT numerical forecasts by experienced forecasters (Desmarais *et al.*, 1978) indicated little, if any, difference between the two for the summer test period; during the winter test period, in those cases where the SAT and NOSAT forecasts differed (only 26% of all the cases), the SAT forecast was judged the better forecast almost $\frac{3}{4}$ of the time. From subjective evaluation of the usefulness and accuracy of prognostic charts generated from SAT and NOSAT forecasts, and from verifications of precipitation forecasts as might be issued in local forecast operations based on outputs from SAT and NOSAT forecasts, Halem *et al.* (1978) find "beneficial but modest impacts." However, Halem *et al.* (1978) also find that in those regions of the forecast area where the impacts are relatively large ($\geq$ 96 m) in 500 mb height for 72 h forecasts), the impact is positive in seven out of nine cases. In Atkins and Jones (1975), in which positive impact was registered by the satellite soundings, "on no occasion would the forecast of weather issued for the British Isles have been affected by the inclusion of satellite data." Druyan *et al.* (1978), in discussing a forecast for which the rms height errors were significantly reduced by inclusion of VTPR observations in the initial analysis, state that "we would hesitate to claim that the satellite data changed a poor forecast into an accurate one." The picture is not as bad in the Southern Hemisphere. Here, the few available studies suggest that satellite soundings produce greater improvements in the numerical forecasts.

Possible reasons for lack of impact have been discussed by Desmarais *et al.* (1978), Tracton and McPherson (1977), and Druyan *et al.* (1978). Satellite soundings show differences of 2–3°C when compared to radiosonde observations. Temperature analyses that include satellite data show smaller variance than analyses based on radiosonde data alone. Figure 4 (after Desmarais *et al.* (1978)) shows the consistently smaller eddy available potential energy (a measure of tempera-

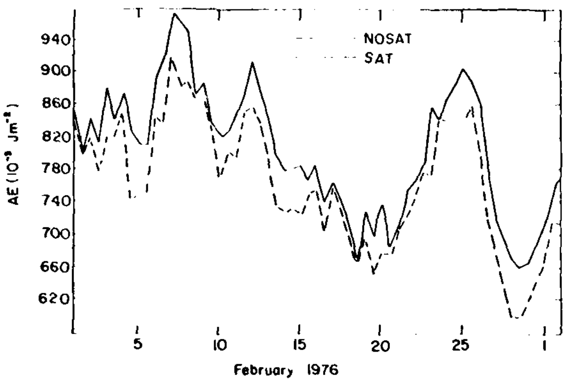

FIG. 4. Eddy available potential energy — AE (10^3 Jm^{-2}) of the atmosphere between 850 and 200 mb, from 20–90°N for SAT and NOSAT analyses. (After Desmarais *et al.*, 1978.)

ture variance) of analyses that include satellite soundings. The satellite sounding data must compete with an initial analysis that is derived from other sources. Apparently the quality of Northern Hemisphere initial analyses, even over data-sparse regions such as oceans, is not improved substantially by the addition of the satellite soundings (incidently, what is usually thought of as a data-sparse region may have significant inputs from aeroplane observations, winds derived from satellite observations, and a reasonably good 12 h forecast); hence, there is a lack of impact on the forecasts. In the Southern Hemisphere, where the quality of the initial analyses is not nearly as good as that in the Northern Hemisphere, the satellite data, despite problems of quality, lead to improved analyses and forecasts.

The above discussion takes a rather pessimistic view of the impact of satellite soundings, at least in the Northern Hemisphere. The optimists may argue, however, that the small, average improvement obtained is significant when compared to the rate at which forecasts have improved over the past decade, that it is becoming more and more difficult to improve the accuracy of forecasts, and that even a small improvement may be significant. They can argue that satellite soundings have led to improvements in the forecasts that might have taken 2–5 years to achieve otherwise, and that forecast capability has been extended by $2\frac{1}{2}$–5 h at the 48 h range. They may have a point.

One should not take the present conclusions as the final word on the subject. The number of impact studies thus far conducted is relatively small, and the number of cases in each study has been barely enough to provide a general picture of impacts. More impact studies are required. Satellite soundings are not point observations like radiosonde observations, but volumetric observations; satellite soundings have their own error characteristics. The weather services of the world have not had much experience with the use of this new type of data. Improved analysis schemes (see, for example, Phillips, 1976) may enhance the impact of satellite soundings. There is also the possibility of reducing the errors of satellite soundings (through increased knowledge of atmospheric transmission characteristics, for example), although the basic problem of poor vertical resolution will always remain for passive observing techniques. Smith (1977, private communication) indicates that the satellite observations, which have a horizontal field of view of the order of 50 km, have been processed to yield a temperature sounding representative of a horizontal area of the order of a 500 km square. As a result of this "horizontal averaging," the horizontal fields of the satellite data are smoother and contain less structure than those typically obtained from analysis of radiosonde observations. Smith (1977, private communication) believes that processing the satellite data at their ~50 km resolution with a few hundred kilometers separation between processed soundings would yield horizontal fields more nearly compatible with radiosonde observations and with the numerical weather prediction models as currently formulated. However, by virtue of the inherent vertical averaging of the satellite temperature-sounding technique, a certain amount of horizontal smoothing is automatically introduced into the analyses. In addition, the statistical climatological nature of the retrieval techniques may also suppress horizontal structure. To what extent the processing of the satellite data at their basic ~50 km horizontal resolution can restore the actual horizontal structure of the temperature field remains to be seen. In any case, the TOVS (TIROS Operational Vertical Sounder) on the third generation polar satellite system of NOAA, the TIROS-N (the first TIROS-N was launched on 13 October 1978), should provide a wealth of data for further impact studies.

Note added in proof: At the time this paper was written, the results of the recent American impact tests were available only in report form. Summaries of these studies are beginning to appear in the scientific journals. Some of the GISS results appear in [illegible] *et al.* (1979b). One new result is based upon subjective evaluation by experienced forecasters of NOSAT and SAT forecasts for the winter test period. The GISS forecasters find that, in those cases where there were differences in the SAT and NOSAT forecasts of 500 mb geopotential height (36% of total cases), the SAT forecast was the better one about $\frac{2}{3}$ of the time. The NMC impact work is reported Tracton *et al.* (1979a) and Tracton *et al.* (1979b).

TIROS-N, launched on 13 October 1978, with the third generation of vertical temperature sounding instruments on board, is capable of providing 10 000 soundings a day. However, since redundant observations in polar regions are not processed, the total is reduced to 8000 per day, of which 2000 are transmitted via the Global Telecommunications System (GTS). The TIROS-N vertical sounding system is described by Smith *et al.* (1979), and an early evaluation of the TIROS-N temperature soundings is given by Phillips *et al.* (1979). Both papers appear in this issue of the BULLETIN. Impact studies are planned for the future.

TIROS-N was joined in space on 27 June 1979 by NOAA-6, the second in this new series of U. S. operational orbiters. When the NOAA-6 sounding system becomes operational, the two satellites will provide 4000 soundings per day over the GTS.

The GISS group that performed the NASA impact studies is now at the Laboratory for Atmospheric Sciences, NASA Goddard Space Flight Center.

Acknowledgments. I would like to thank the following for providing information with respect to my query on the impact of satellite soundings: Weather Bureau, Republic of South Africa; Meteorological Service, France; Meteorological Service, Federal Republic of Germany; Bureau of Meteorology, Australia.

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